NASA AERONAUTICS RESEARCH INSTITUTE

Biomimetic Fly Eye Sensor for Real-time Target Tracking

NASA Aeronautics Research Mission Directorate (ARMD)

2015 Seedling Phase II Technical Seminar

November 17 & 19, 2015

Outline

- Motivation
- The Innovation (Compound Eye Sensor)
- Technical Approach
  - Sensor testbed and support tools
  - Sensor characterization and performance
  - Tracking algorithms
- Next Steps
- Impact on Aeronautics & Other Applications

The Compound Eye Team

- Susan Frost (NASA Ames Research Center)
  - Principal Investigator (PI)
- George Gorospe (SGT, Inc.)
  - Testbed, Sensor development
- Chris Teubert (SGT, Inc.)
  - Simulation, Tracking Algorithm Development
- Hiro Kumagai (Aerospace Computing, Inc.)
  - Testbed development, Signal Processing Development
- Leslie Yates (Aerospace Computing, Inc.)
  - Calibration Method Design

Interns

Jason Watkins
Guilherme de Oliveira
John Vo
Karen Trinh
Richard Gil
Gwen Lynch
Jason Renwick

Two more for Spring 2016

Motivation

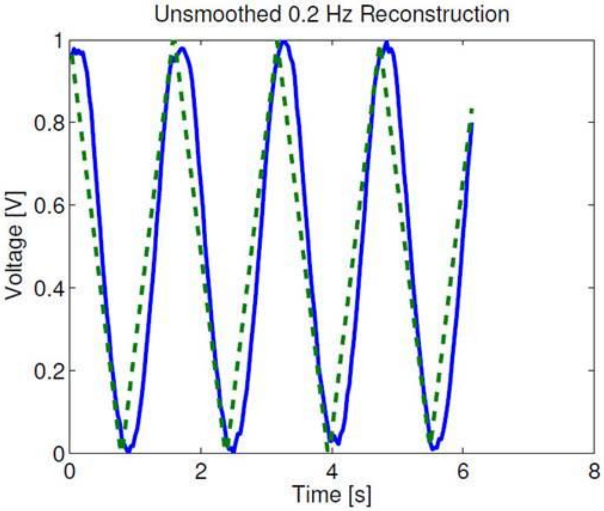
Need measurement of wing deformation for next generation energy efficient aircraft configurations

Helios before crash

State-of-the-Art: Strain gauges, fiber optic strain sensors, accelerometers, GPS, traditional cameras

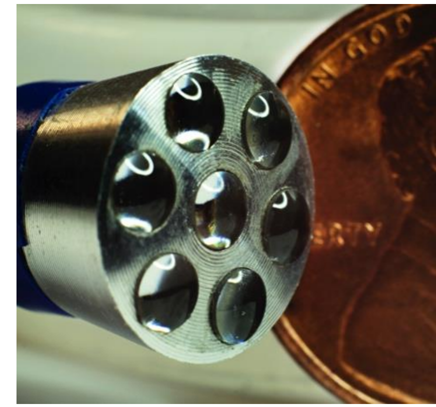
Background

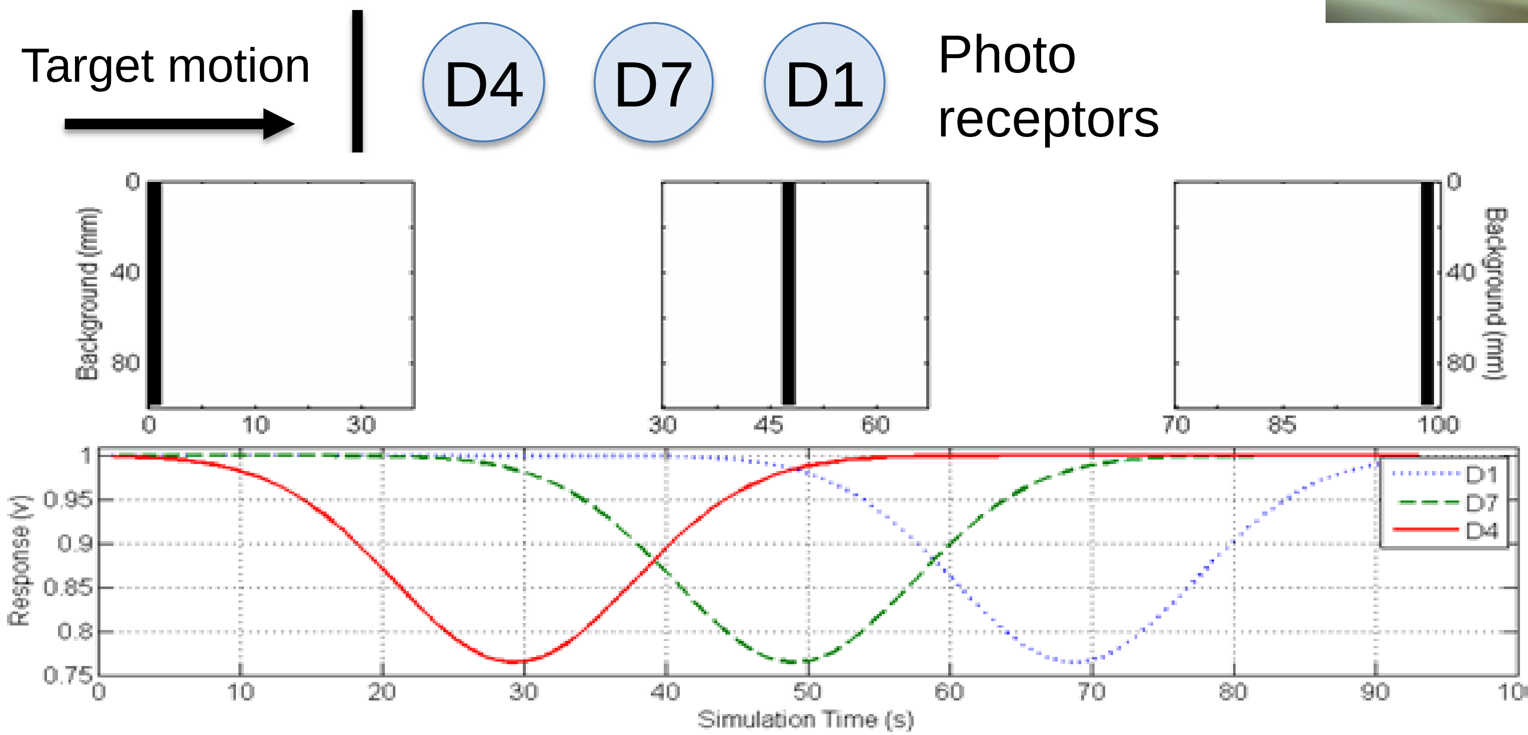
- Phase I effort: Developed and built a compound eye sensor based on the vision system of the common house fly with University of Wyoming partners
- Initial studies demonstrated sensor's response (in terms of voltage) to a simple target



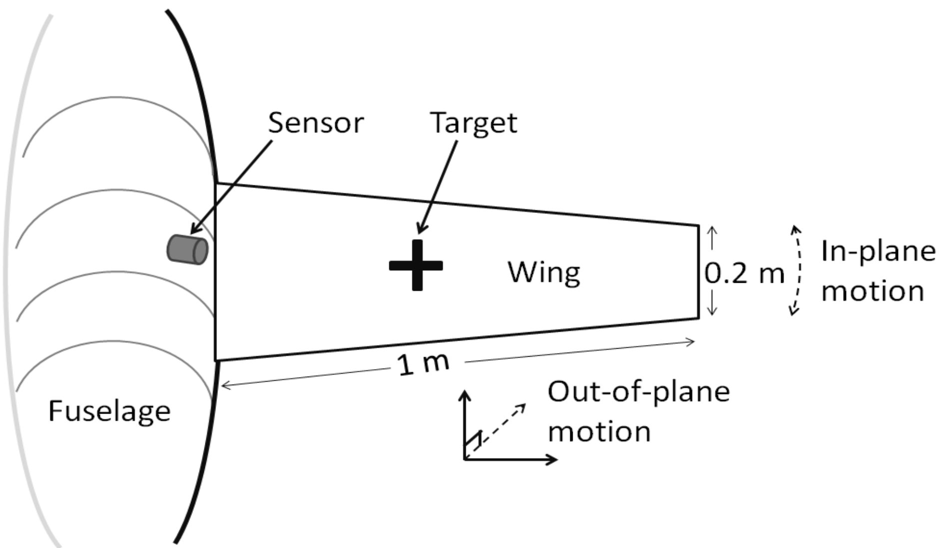
Introducing the Compound Eye Sensor

- Motion hyperacuity, (ability to track motion at sub-pixel increments)
- Fast processing speed
- Low computational overhead
- Low power requirements
- Superior performance in low light & low contrast
- Small form-factor, low mass





Implementation of Technology



- Sensor system that can track a target, providing output that relates directly to target position
- Robust to changing background
- Mission adaptive sensor (modular & scalable)

Single integrated sensor system with superior performance for its weight and power requirements when compared to existing sensor systems

What is needed to get there

Final Compound Eye Sensor Design that performs well in expected environments

Robust Real-Time Tracking Algorithm that can operate in dynamic environment

Detailed Understanding of Compound Eye Sensor Performance and Behavior

Noise attenuation techniques: filters, ambient light adaptation, etc.

Packaging: Hardware, software, target, communication, processes

Compound Eye Sensor Performance Analysis

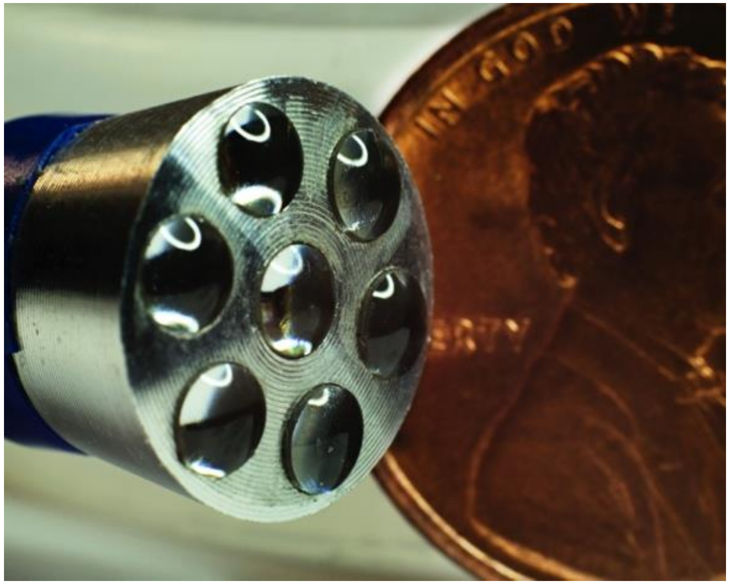
Support Tools

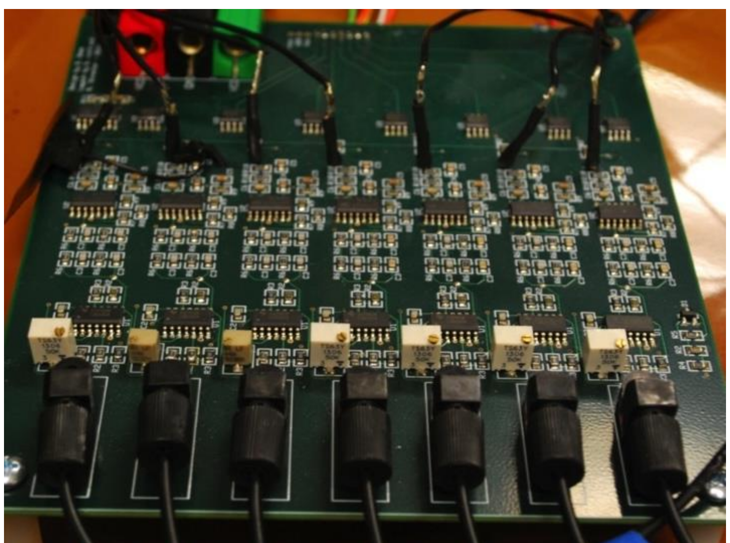
- Experimental Infrastructure
- Research Support Software
- Detailed Optical Simulation
- MySQL Research Testbed Toolbox

Experiments

- Static Characterization Experiments
- Dynamic Characterization Experiments
- Distance Studies
- MORE

Sensor Benchmark Testing





Sensor Platform Benchmark Testing:

Performance (FOV, response, etc.)
Uncertainties (lens position, etc.)
Processes (algorithms, calibration, etc.)
Additional Factors (signal noise, etc.)

Driven decisions:

Application
Software Development
Simulation
Hardware Development
Manufacturing Methods

Sensor Development Testbed

Sensor Platform
Benchmark Testing:

- Performance
- Uncertainties
- Processes
- Additional Factors

Testbed Variables:

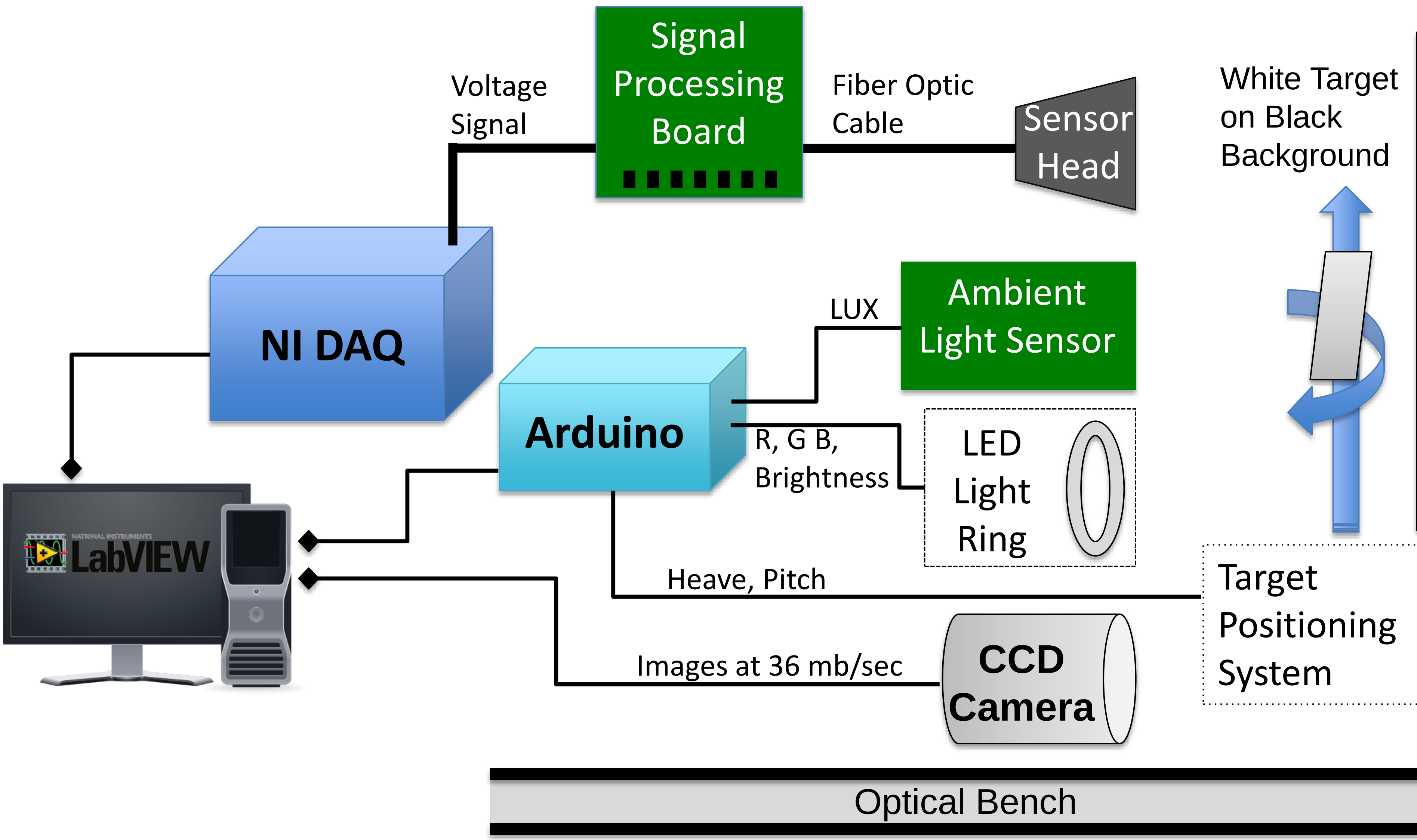
- Static / Moving target (Heave, Pitch)
- Vibrating Target
- Light Level / Light Wavelength
- Low Contrast Target / Background
- Sensor Orientation

Optically Isolated Test Environment

- Understand sources of sensor noise
- Understand background noise

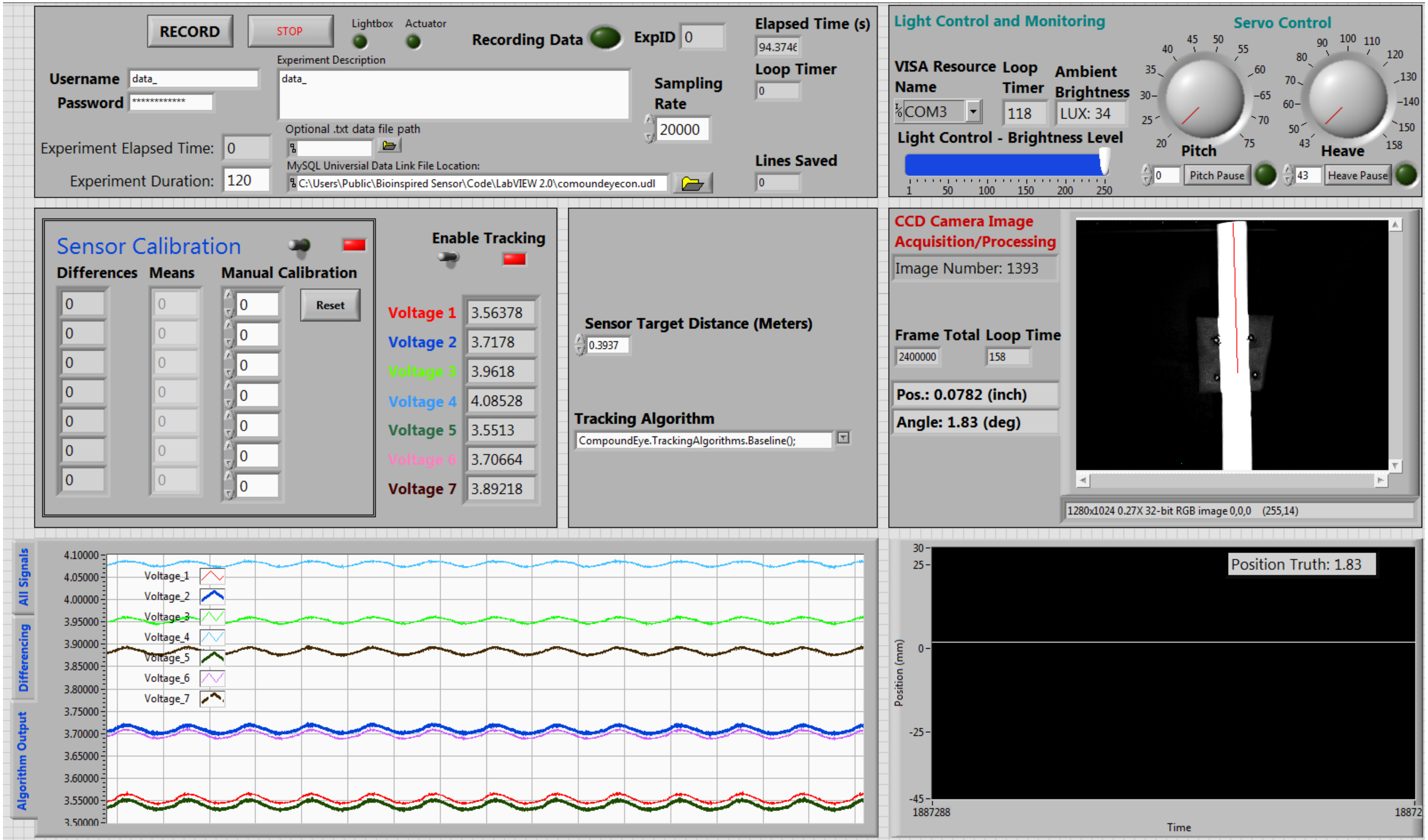
Background noise is a HUGE challenge in developing the Compound Eye Sensor

Testbed Block Diagram



Experiment/Control Interface

LabVIEW VI Control GUI

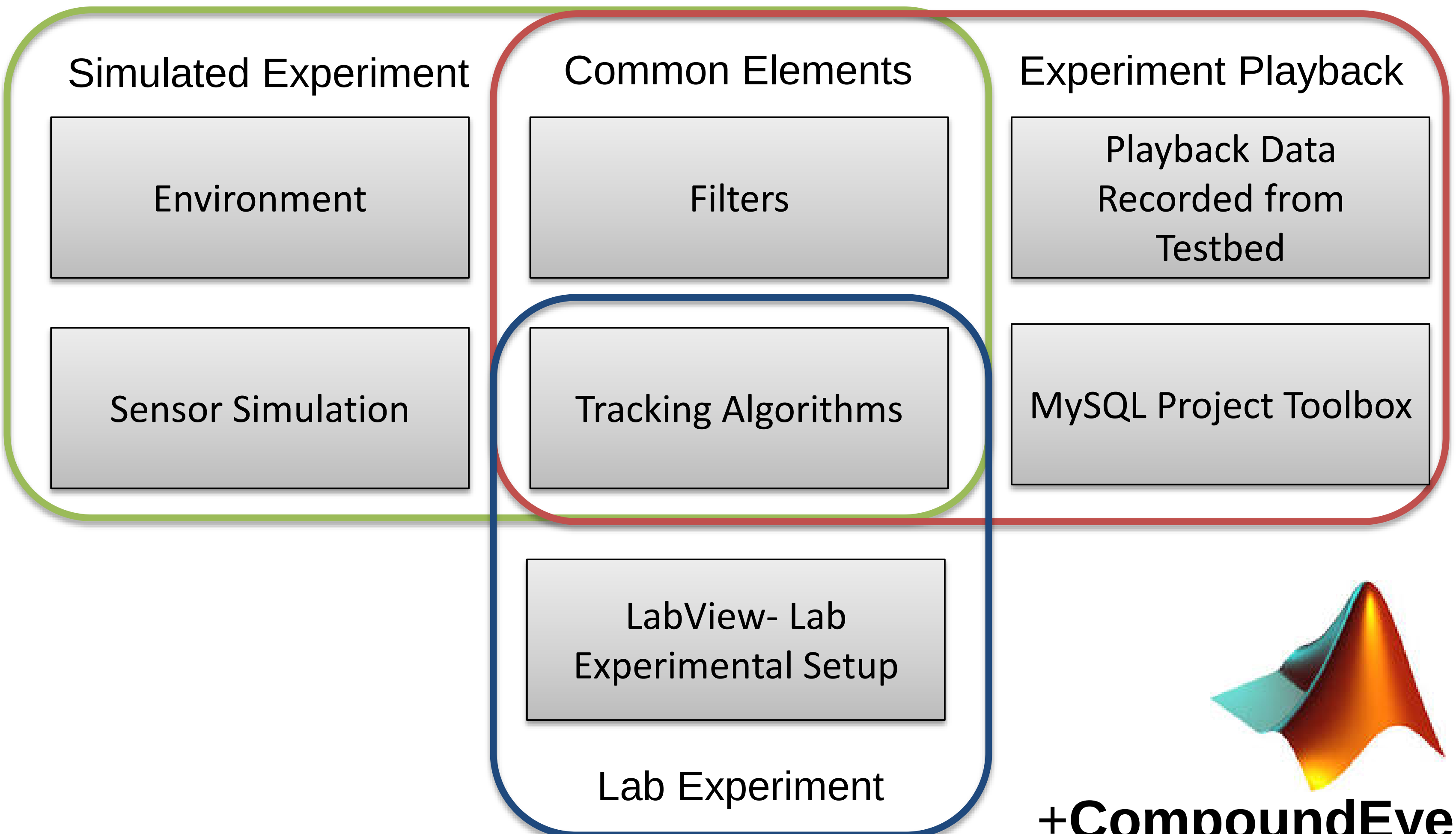


Compound Eye Simulation and Research Support Software

Extensive tool suite developed to aid with understanding the behavior of Compound Eye Sensor, development and testing of tracking algorithms, evaluation of performance for specific applications, and the design and evaluation of next generation Compound Eye sensors

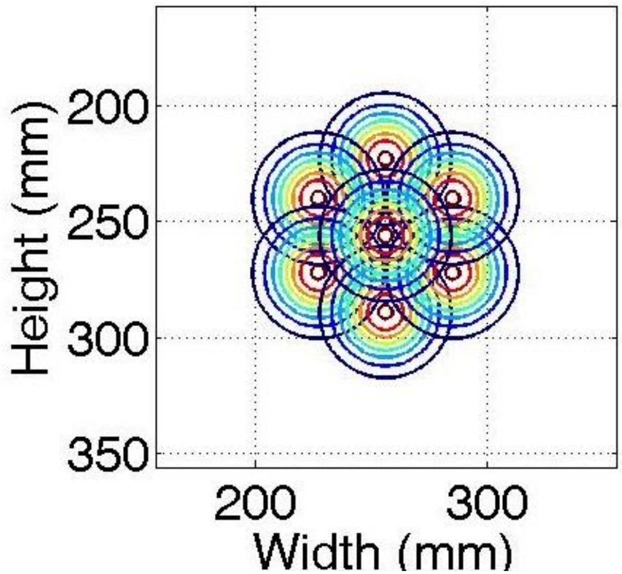
Physics-Based Compound Eye Simulation	Data Playback	Compound Eye Performance Visualization Tools
Behavior Metrics	Tracking Algorithm Metrics	Noise Addition
Data Filtering	Tracking Algorithm Development Tools	Others

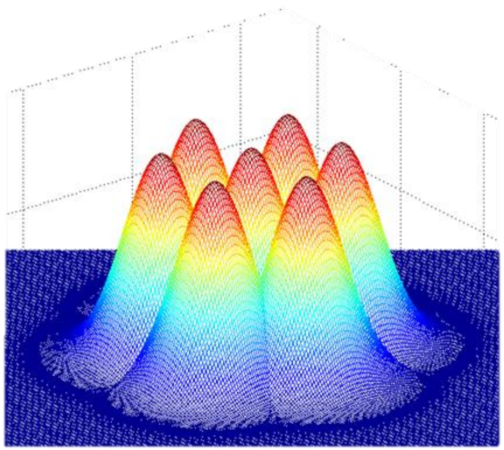
Compound Eye Simulation and Research Support Software



+CompoundEye

Simulating the Compound Eye Sensor

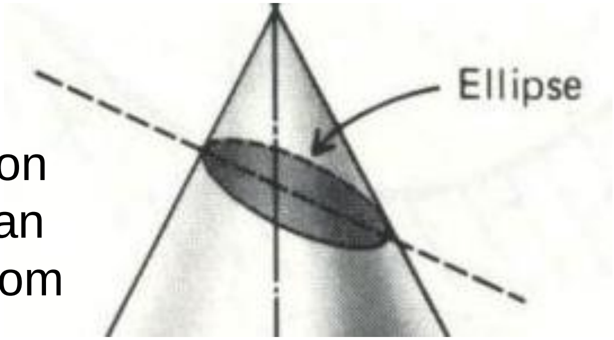




R = S * I

$$\mathbf{S} = e^{-0.5\left(\frac{X'}{\sigma_{X'}}^{2} + \frac{Y'}{\sigma_{Y'}}^{2}\right)}$$

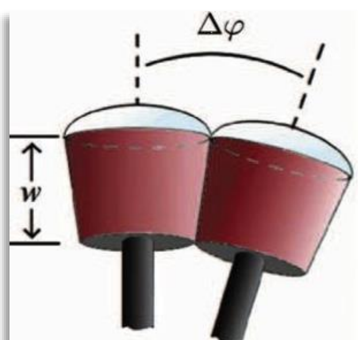
R: **Response Matrix –** The amount of light sensed from each point on the target plane
S: **Sensitivity Matrix –** The response at any point on the target plane. Represented by stretched Gaussian
I: **Image Matrix –** The amount of light emanating from each point on the target plane

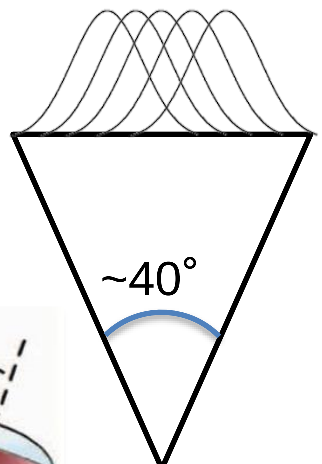


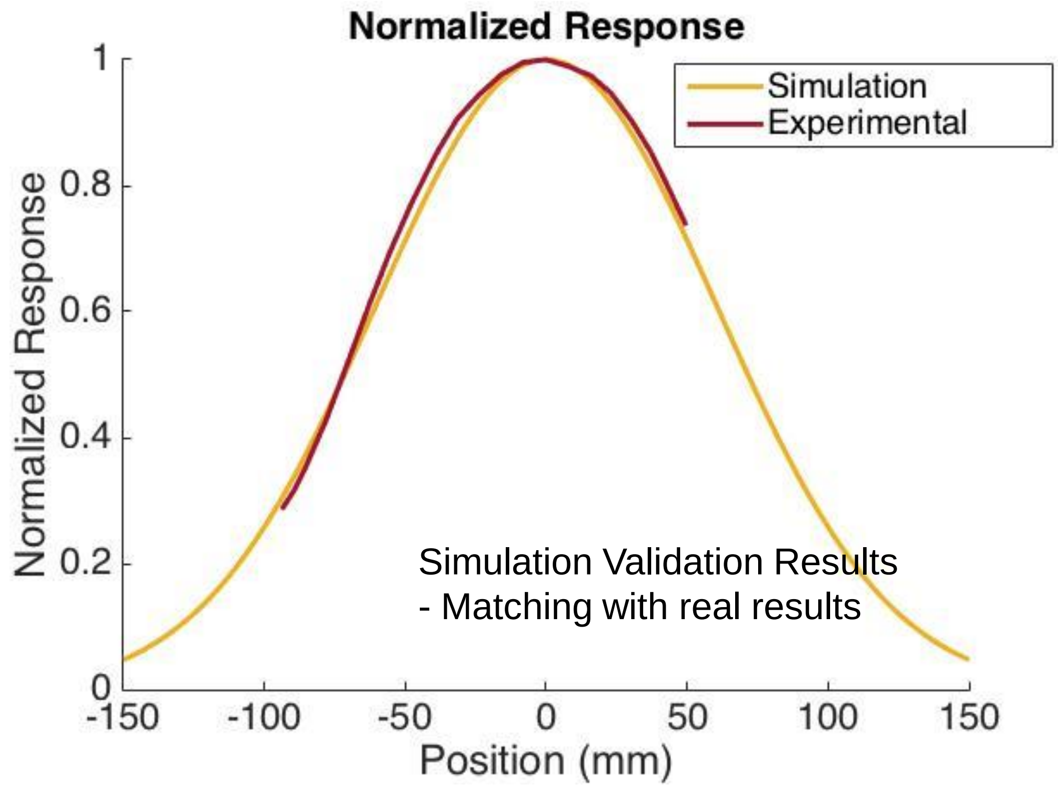
Simulating the Compound Eye Sensor

Field of View: *The extent of the observable world that produces a **useful** response in the output of the compound eye sensor*

Diode Response: near-Gaussian (σ =7.5°)
Total sensor practical field of view: 40°
Ideal sensor maximum field of view: 42°

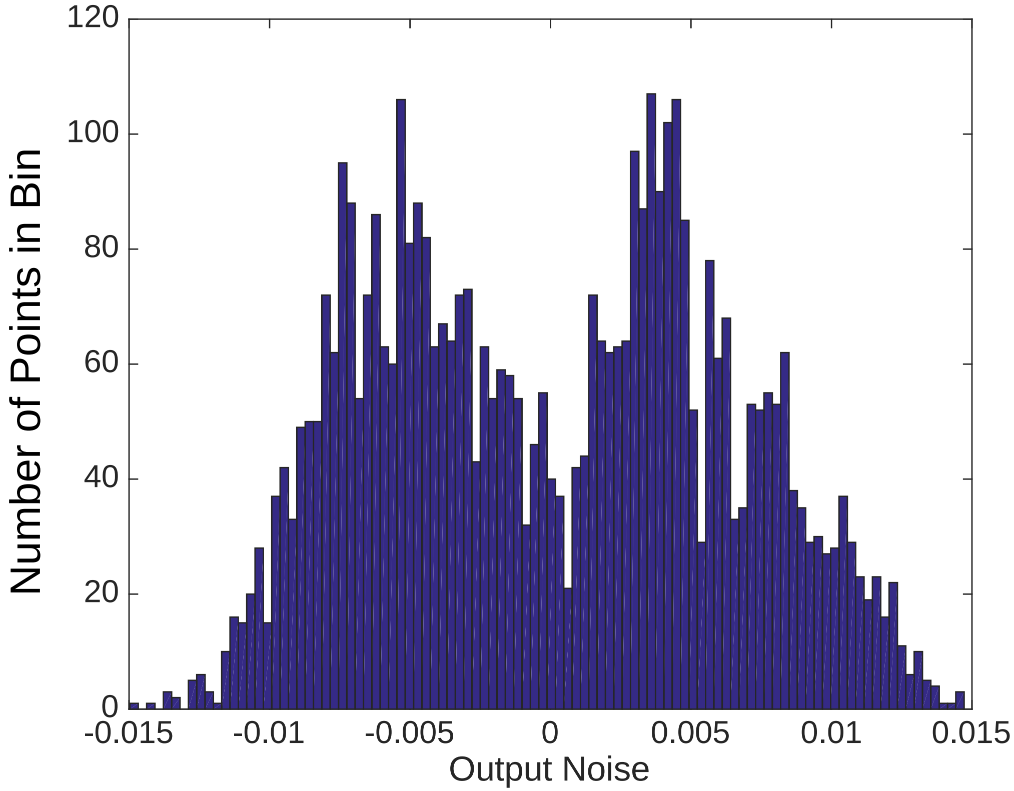






Noise Characterization

Noise Characteristics
- Shape: Bimodal normal distribution
- Maximum Amplitude: ± 0.015 V
- Try to maximize the signal-noise ratio



Potential Noise Sources
Light Flickering
Electrical Noise
Sensor Noise
Vibrations

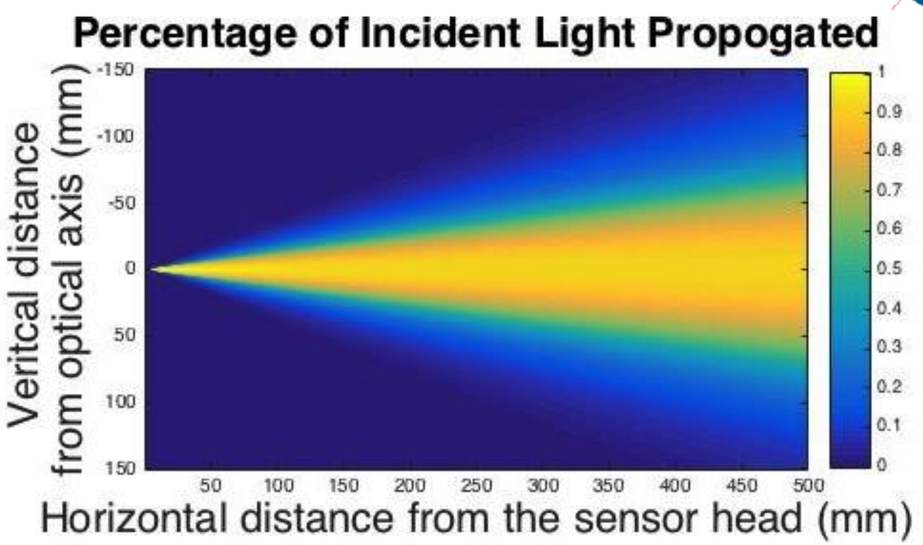
Factors that affect Signal Strength
Sensor-target distance
Target size, reflectivity
Target-background contrast
Lighting Levels/Wavelength

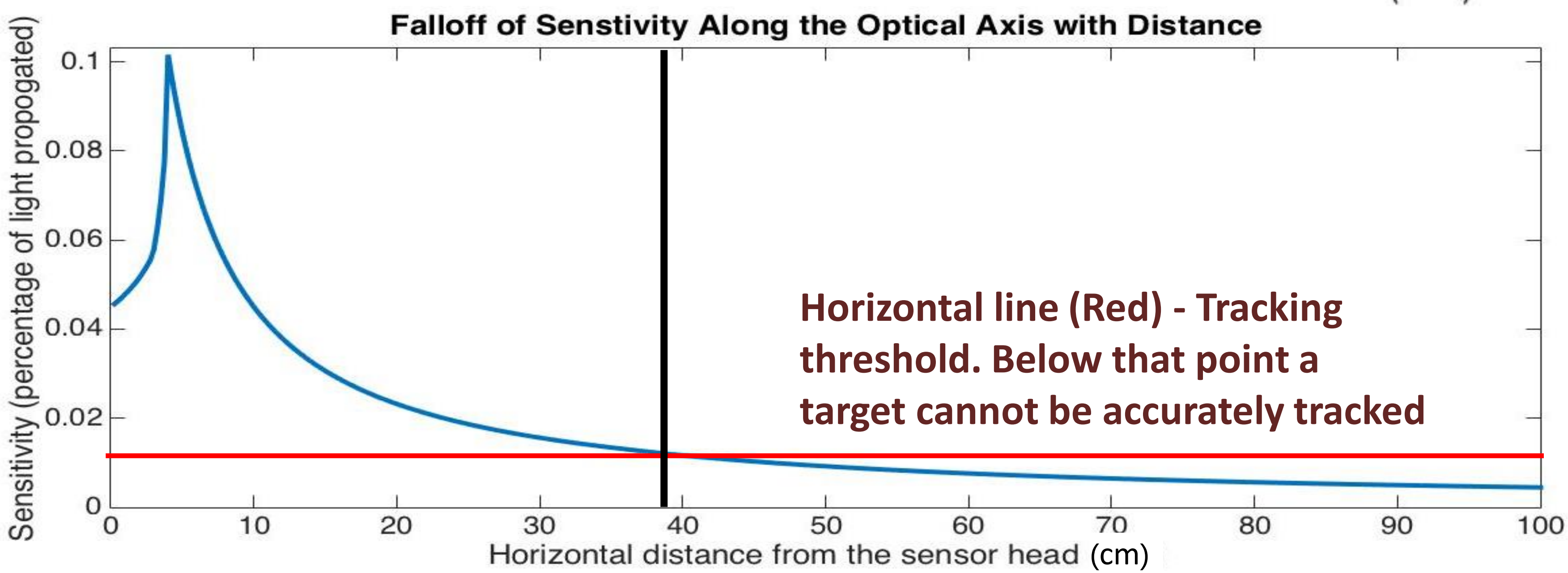
Behavior - Distance

$$T_{Track} = f(D, L, S, N, \ldots)$$

T_{Track}: Tracking threshold

D: Sensor-target distance
L: Light levels
S: Target size
N: Noise levels

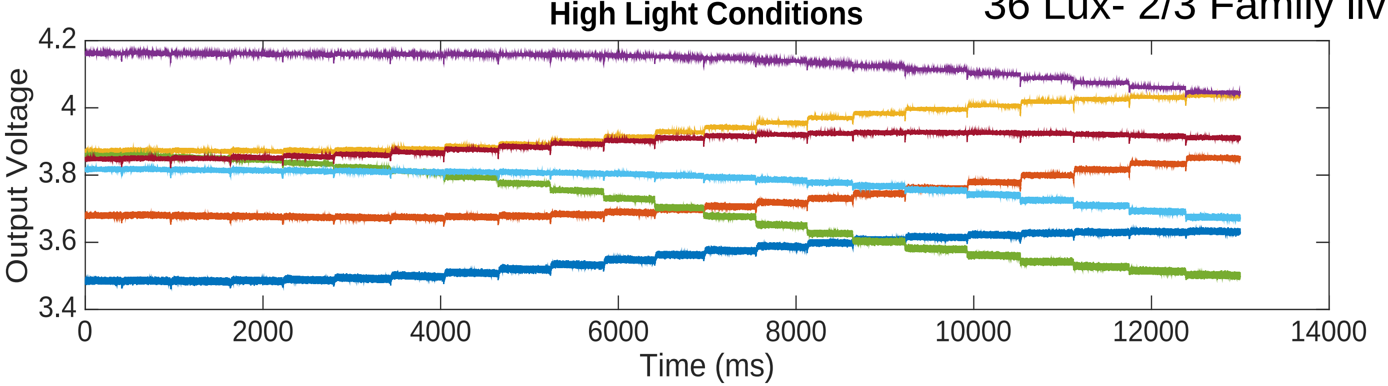


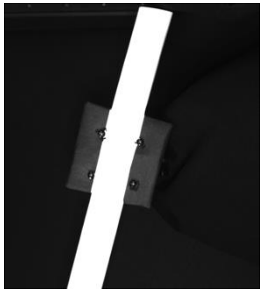


Behavior - Low light

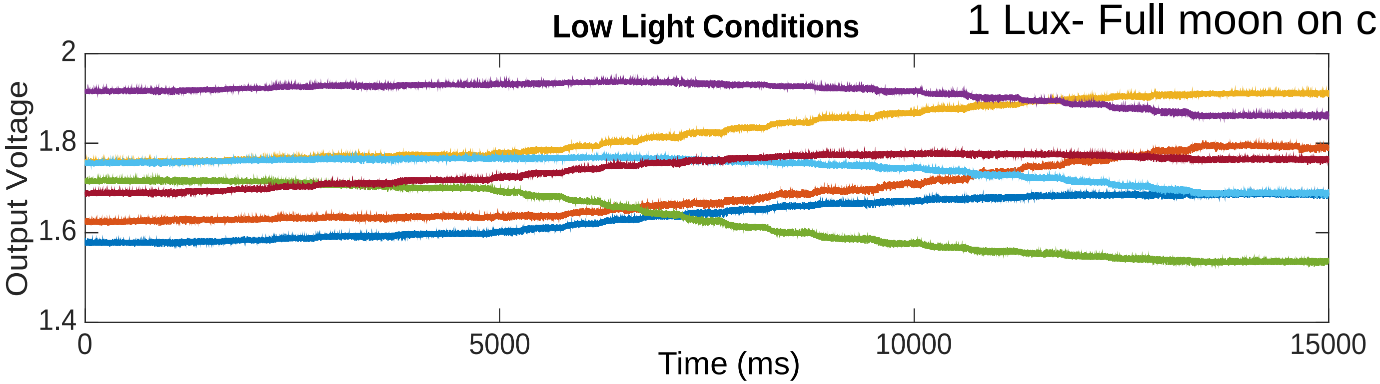
- The compound eye has shown improved capability when tracking in low-light conditions
- The bottom experiment shows the sensor output for a moving target at 1 Lux ambient light - this is far below the level that the camera tracking system could detect
- Motion: 70 mm at ~0.3 Hz

36 Lux- 2/3 Family living room lighting



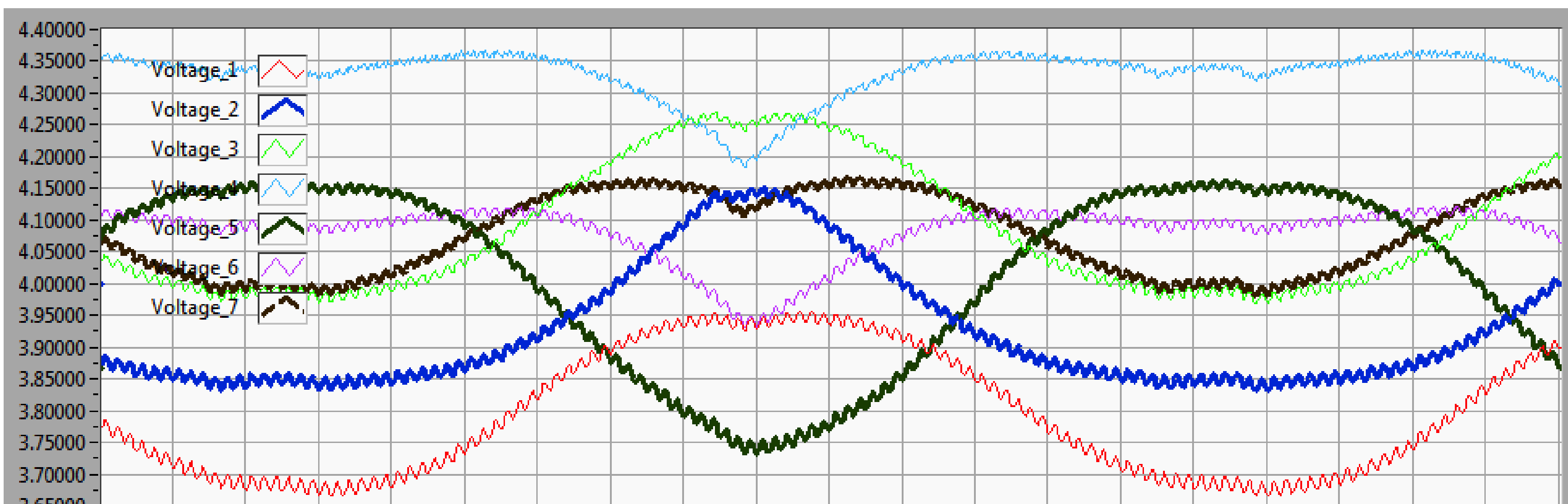


1 Lux- Full moon on clear night



Behavior - High speed

- For high-speed motion, the camera showed blurring – this amounts to information loss
- With a 5 ns rise/fall time, the compound eye sensor is able to detect motion in smaller time increments – no information loss
- Motion: 70 mm at ~1 Hz
- Image: 1280 x 1024 at 15 fps



Data Management

- Challenge in storing, managing, and sharing data collected by lab and simulated experiments
- We created a database, a standard file format, and set of generic tools and instructions

NATIONAL INSTRUMENTS LabVIEW

Tables

Data Table
Dynamic, changing

Experiments Table
Static, unchanging

Matlab Tools (+MySQL)

setupDatabase | connection | getFields

getExp | downloadExp | createExp

sendData

What is needed to get there

Final Compound Eye Sensor Design that performs well in expected environments

Robust Real-Time Tracking Algorithm that can operate in dynamic environment

Detailed Understanding of Compound Eye Performance and Behavior

Noise attenuation techniques such as filters, ambient light sensors, etc.

Packaging: Hardware, software, target, communication, processes

Baseline Tracking Algorithm

Baseline Real-Time Tracking – Early 2015

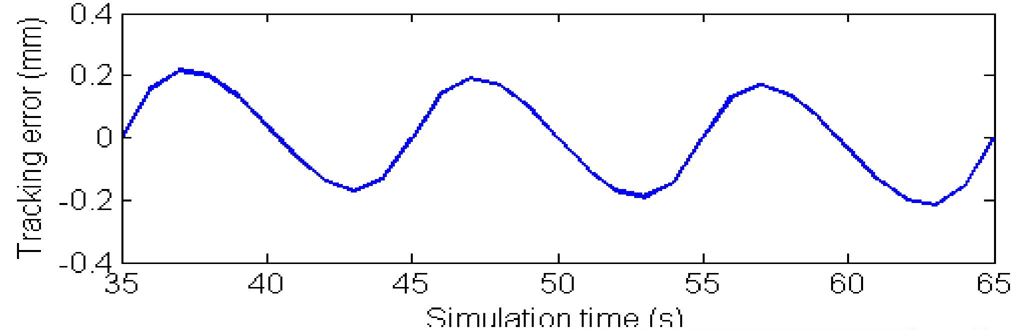
- First draft simple tracking algorithm- Considered a "Starting Point"
- Uses linear portion of output graph to estimate position

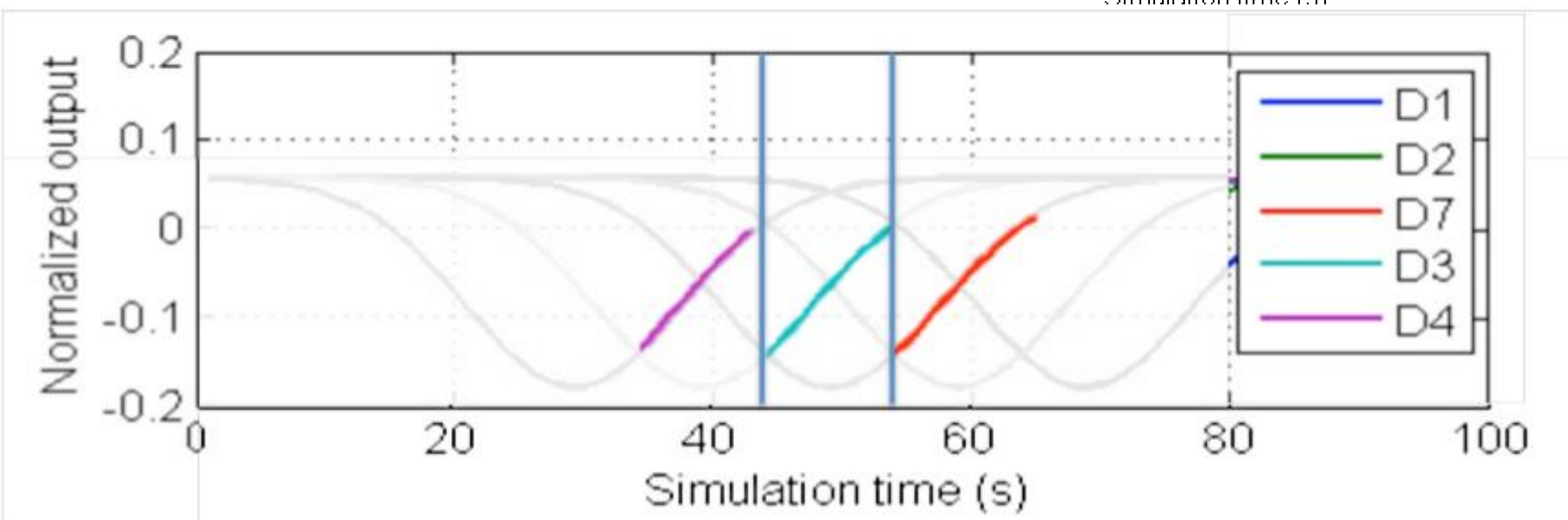
Limitations

- Peripheral tracking
- Accuracy near peaks
- Requires "Tuning" for environment

Strengths

- Speed
- Simplicity
- Real-time Tracking





Real-Time Tracking Algorithms

Unscented Kalman Filter (UKF) with Gaussian mapping (Summer 2015)

- Tried with Unscented Kalman Filter (UKF) and Particle Filter- UKF showed similar accuracy with much less computational demand
- Very accurate when exact knowledge of background is available

Limitations

- Does not work with dynamic backgrounds

Strengths

- Quick capture time
- Peripheral Tracking

UKF using Ambient Light Sensing (October 2015)

- Extra mapping with ambient light sensor to increase robustness with dynamic lighting
- Uses real data collected in controlled environment

Limitations

- Still has limitations in non-uniform dynamic backgrounds

Strengths

- Performance with dynamic lighting
- Quick capture time
- Peripheral Tracking

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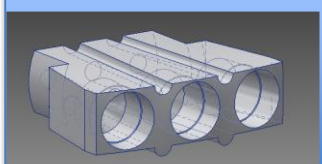
Next Generation Compound Eye Sensor

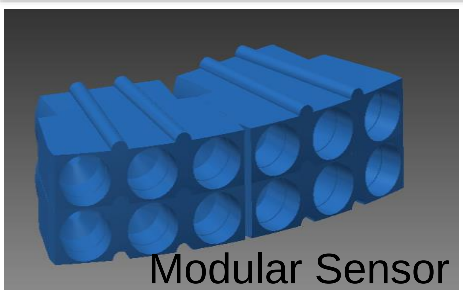
Current Generation Compound Eye Sensor

Application Specific Performance Enhancements:

- Measurement at greater distances
- High or very high gain for low-light settings
- Measurement accuracy
- Multiple target tracking
- Advanced calibration methods



Next Generation Compound Eye Sensor

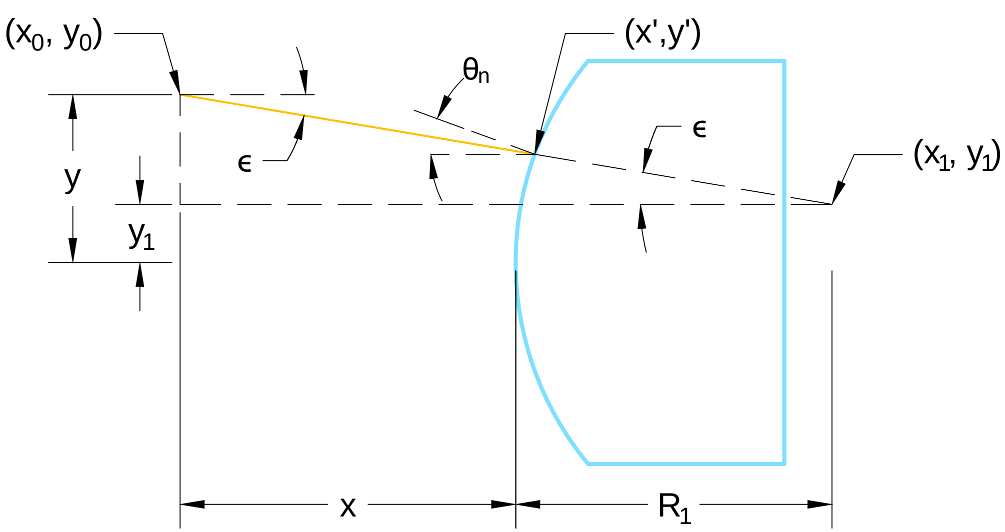


Increased Value:

- Low cost optical solution
- Low processing overhead
- Low Power/ Low Weight/Small Volume
- Robust operation
- Modular and reconfigurable
- Standard software
- Digital or Analog photo detectors

Detailed Optics Tool

- Uses Ray Tracing through the Compound Eye Sensor to determine the behavior of a new sensor design
- Results plug into simulation tool
- Designed by interns
- Ran on Pleiades Supercomputer (at no cost)
- Validated against experimental data



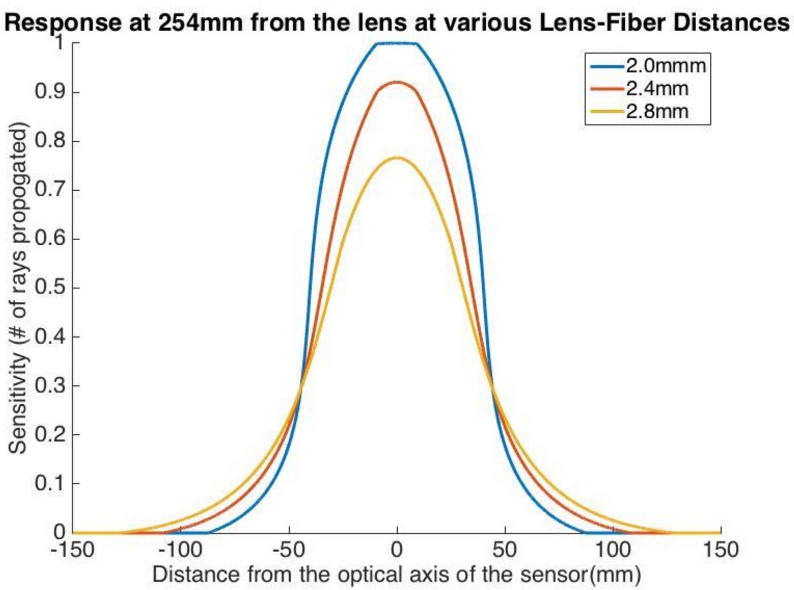


Photo Detector Study

IF-D91 High-Speed Photodiode Detector

- Up to 100 Mbps data rate
- Optical Range: 450-1100 nm
- Fast rise and fall times

In Use

IF-D High-Sensitivity Phototransistor Detector

- Up to 25 kbps data rate
- Optical Range: 400 – 1100 nm
- High internal gain

IF-D93 Very High-Sen. Photodarlington Detect

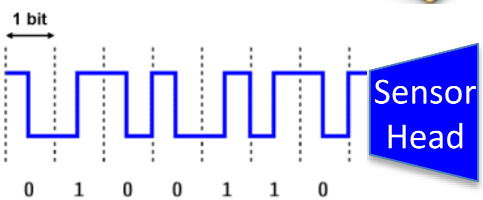
- Up to 1kHz data rate
- Optical Range: 400-1100 nm
- Very high internal gain

Avago APDS-9301 Ambient Light Photo Sensor

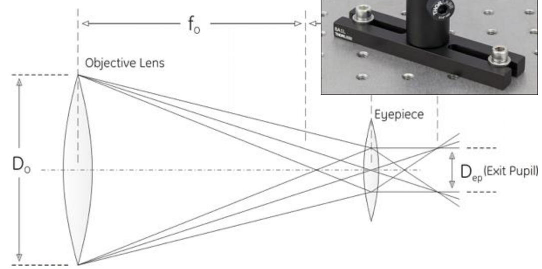
- Digital signal output with direct I2C interface
- Human-eye approximate response in units of LUX

Research Directions

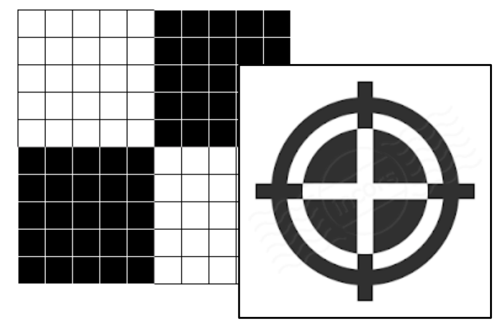
Digital Sensor
Independent Digital Sensors



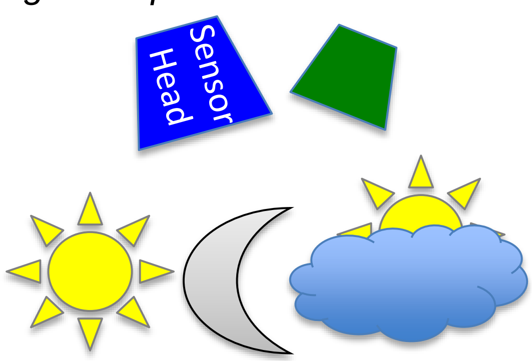
Magnification
For Extended Range



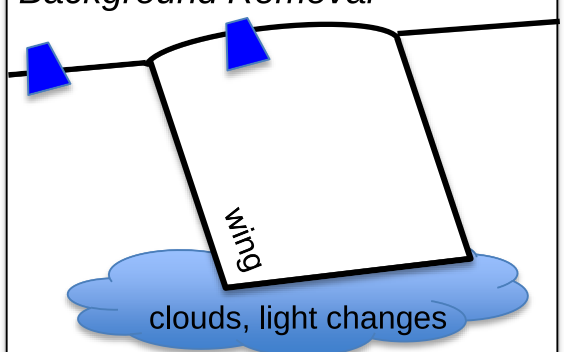
Calibration
Advanced Calibration Methods



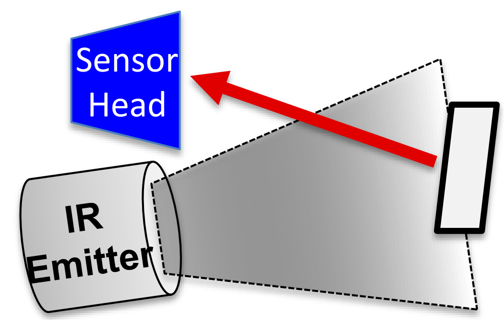
Ambient Light Sensor
Light Adaptation



Dual Sensors:
Background Removal



Active Sensor:
IR Emitter / Receptor

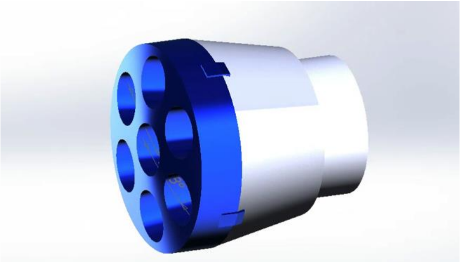


Dissemination

- Compound Eye Sensor Dissemination
  1) *Compound Eye Sensor for Real-time Aircraft Wing Deflection Measurement* – Accepted Proceedings AIAA SciTech Forum, January 2016
  2) *Real-time Measurement of Aircraft Wing Deflection using an Optical Sensor* – Submitted IFAC Journal of Control Engineering Practice Special Issue on Aeronautics Applications, October 2015
  3) *Bioinspired Optical Sensor* – Poster at NASA Ames Instrumentation Workshop, September 2015
  4) *Biomimetic Optical Sensor for Aerospace Applications* – Proceedings SPIE Sensing Technology & Applications Conference, April 2015
  5) *Bioinspired Compound Eye Sensor* – Oral presentation at UC Berkeley, March 2015
  6) *Bioinspired Optical Sensor for Wing Position Sensing* – NASA-wide Aeroservoelasticity Summit, April 2015
  7) *Natural Systems Inspiration for Aeronautics Applications* – Oral presentation at Embry-Riddle Aeronautical University, February 2015
  8) *Bioinspired Optical Sensor* – Poster at NASA Ames Open House February, 2015
  9) *Biomimetic Optical Sensor for Real-Time Aircraft Wing Deflection Measurement* – Proceedings AIAA SciTech Forum, January 2015
  10) *Natural Systems Inspiration for Aeronautics Applications* – Oral presentation at INCOSE Natural Systems Working Group Meeting, January 2015 and Embry-Riddle Aeronautical University February, 2015
  11) *Localization of a Moving Target Using a Fly Eye Sensor* – Proceedings Biomedical Sciences Instrumentation, May 2014
  12) *Biomimetic optical sensor for real-time measurement of aircraft wing deflection* – M.S. Thesis, Electrical Engineering, University of Wyoming, May 2014
- New Technology Reports
  – Compound Eye Research Package - NTR#1446568279
  – MySQL Research Testbed Toolbox - NTR#1446570361
  – Real-Time Tracking Algorithms - NTR#1447452488
- Proposed application work that was funded by U.S. Geological Survey ($70K)
- Mentored 7 student interns

Summary

- Detailed Understanding of Sensor Performance and Behavior
  - Designed & built sensor testbed with integrated experiment control and data collection and storage
  - Performed detailed characterization of the sensor through experiments and simulation
  - Tested sensor to application requirements
  - Comparison with state-of-the-art (CCD)
- Development to Support Applications
  - Real-Time target tracking algorithms for position
  - Sensor calibration studies for active targets
  - Performance improvement studies
- Design of Next Generation Sensor
  - Sensor head design
  - Photodetector studies
  - Signal processing board



NextGen sensor head

Next Steps

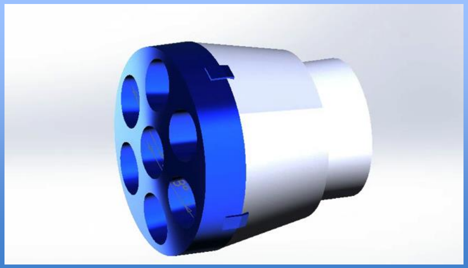
Short Term

- Improved real-time tracking algorithms – Accuracy, capture, rotation
- Improved noise filters
- Gen 2.0 sensor: Updated electronics & sensor head
- Journal paper on detailed characterization & performance studies
- Complete tracking algorithm testing suite

Mid Term

- Gen 3.0 sensor: Fully digital sensor
- Flight test (AFRC)
- Multiple target tracking
- Manufacturing methods
- Earthquake fault monitoring application research with USGS
- Deployable product
- Modular Sensor

Completed Product



Impact

- Next generation N+3 energy efficient civil transport aircraft
  - Wing shaping feedback control for increased aerodynamic performance
  - Flutter & structural overload control for increased safety & reduced weight
  - Shape control for novel aeronautics structures (ARMD CAS MADCAT Project)
- Structural health monitoring
  - Improved performance and reduced cost compared with state-of-the-art
  - Nonintrusive, easily deployed position and vibration monitoring
  - Improved fault detection and accommodation through continuous monitoring of multiple locations
  - Wind turbines, large civil structure monitoring (bridges, buildings, etc.)
- Real-time structure position monitoring in wind tunnel
- UAV horizon monitoring, path following
- Low cost earthquake fault monitoring (U.S. Geological Survey funded project)
- CubeSAT maneuvers for space debris removal
- Solar panel deformation monitoring for increased energy capture
- Robotic machine vision (tensegrity)